



Retention of Compressive Residual Stresses Introduced by Shot Peening in a Powder Metal Disk Superalloy

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Abstract

The fatigue lives of disk superalloys can be increased by shot peening their surfaces, to induce compressive residual stresses near the surface that impede cracking there. As disk application temperatures increase for improved efficiency, the persistence of these beneficial stresses could be impaired, especially with continued fatigue cycling. The objective of this work was to study the retention of residual stresses introduced by shot peening, when subjected to fatigue and high temperatures. Fatigue specimens of powder metallurgy processed nickel-base disk superalloy ME3 were prepared with consistent processing and heat treatment. They were then shot peened using varied conditions. Strain-controlled fatigue cycles were run at room temperature and 704 °C, to allow re-assessment of residual stresses.

Introduction

The low cycle fatigue (LCF) lives and predominant failure modes of powder metallurgy (PM) nickel-base superalloy compressor and turbine disks can be influenced by environmental exposures during service (Refs. 1 to 3). In some conditions, this can shift failure initiation sites from internal sites to exposed surfaces. It has been shown that for fixed fatigue test conditions, surface-initiated failures produce significantly lower fatigue lives than internally initiated failures (Refs. 4 and 5). There, the environment can accelerate both the initiation and growth of fatigue cracks.

Shot peening is a widely used surface enhancement process which produces beneficial compressive residual stresses on treated metallic surfaces (Ref. 6). This process has been adopted in many cases to improve the fatigue life of nickel-base disk superalloy components by reducing the propensity for cracks to initiate at machined surfaces (Refs. 7 and 8). Yet, the cold work produced by shot peening can accelerate relaxation of the compressive residual stresses during exposures at turbine temperatures and

increase sensitivity to overload relaxation (Refs. 9 and 10). It has been conclusively shown that shot peening with reduced coverage and correspondingly reduced cold work could help to minimize these effects and help maintain fatigue life at elevated temperatures in cast and wrought superalloy 718 (Ref. 11). However, optimal shot peening conditions for newer generation powder metal superalloys, which are capable of higher service temperatures, have not been clearly defined. This is so even for those powder metal superalloys prepared with coarse grain microstructures, to be more resistant to creep, stress relaxation, and dwell fatigue crack growth.

An in-depth study of shot peening conditions versus fatigue life of a higher temperature, more creep resistant powder metal disk superalloy René 88DT prepared with coarse grain size (Ref. 12) indicated these competing considerations were still operative. The compressive residual stresses produced by shot peening were considered beneficial in suppressing the initiation and growth of fatigue cracks at the specimen surface, while the accumulated plastic strain produced by shot peening was considered harmful as plasticity associated with fatigue damage. The effects of plasticity on relaxation of compressive residual stresses were also considered here. More recent work on another powder metal disk superalloy RR1000 prepared with coarse grain size (Ref. 13) has focused highly refined experiments on characterizing dislocation hardening generated in grains near the surface which has been shot peened. Yet, many current models trying to take credit for shot peening on fatigue life of superalloy disks are based on fracture mechanics (Refs. 14 and 15), and they model cracks initiated and driven predominantly by stresses. Therefore, retention of residual stresses was the primary focus of the present work.

The objective of this work was to determine the persistence of the beneficial compressive residual stresses introduced by shot peening of a powder metallurgy disk superalloy ME3, when subjected to fatigue at high temperature. Fatigue specimens were shot peened under varied conditions, with relatively low levels of coverage selected, in hopes of minimizing stress relaxation due to excessive cold work. Resulting roughness, residual stress and cold work were assessed. Selected specimens were then fatigue cycled, and again evaluated.

Materials and Procedures

Material Processing

The ME3 material was obtained as atomized alloy powder, then consolidated, extruded, and isothermally forged into planar disks. Its composition in weight percent was 3.36Al-0.02B-0.053C-21.04Co-12.95Cr-0.036Fe-3.71Mo-0.8Nb-0.022O-0.033Si-2.4Ta-3.83Ti-2.07W-0.045Zr-bal. Ni. Specimen blanks were then extracted and consistently heat treated in a fixture. They were solution heat treated at 1135 °C for 2 h plus furnace cooled and then 1171 °C for 1.5 h plus air cooled. The second step of this solution heat treatment was above the solvus of the γ' precipitates (Ref. 16), to allow more gamma grain growth. They were subsequently aging heat treated at 843 °C for 4 h and 760 °C for 8 h plus furnace cooled, for full precipitation and growth of gamma prime precipitates. Sections of superalloy 718 were inertia welded to each end of each blank, and the resulting assemblies were then machined at Element Materials Technology of Cincinnati, Ohio by low stress grinding into low cycle fatigue specimens with a uniform gage section of 6.25 mm diameter and 19 mm long. The gage sections were then longitudinally polished to a root mean square roughness (R_{rms}) of less than 0.20 μm .

Shot peening procedures including intensity and coverage calibrations, nozzle design, specimen masking, and other quality control issues were performed according to AMS2432 specifications by Metal Improvement Co., Curtiss-Wright Surface Technologies of Blue Ash, Ohio, using conditioned cut stainless steel wire, with a roughly spherical mean diameter of 360 μm (0.014 in.) after conditioning (CCW14). Specimens were rotated in a fixture while a translating nozzle maintained at a constant angle applied the shot at constant pressure and flow rate, using a computer controlled automated system. As shown in Table 1, shot peening intensities were varied from 8 N to 8 A (~24 N), with coverages of 100 and 300 percent, 100 percent coverage was defined as the time necessary to indent all of the exposed surface, and 300 percent coverage was 3X that time. A central condition of 16 N intensity and 200 percent

TABLE 1.—REGRESSION VARIABLES, PARAMETERS, VALUES, AND SCALED VALUES.

Variable-unit	Parameter	Values		
Intensity-N	I	8	16	24
<i>(Scaled)</i>	<i>I</i>	<i>-1</i>	<i>0</i>	<i>+1</i>
Coverage-%	C	100	200	300
<i>(Scaled)</i>	<i>C</i>	<i>-1</i>	<i>0</i>	<i>+1</i>
Fatigue cycle	F	0		1
<i>(Scaled)</i>	<i>F</i>	<i>-1</i>		<i>+1</i>
Temperature-°C	T	25		704
<i>(Scaled)</i>	<i>T</i>	<i>-1</i>		<i>+1</i>

coverage was also included. For clarity in comparing the effects of varied intensity, the highest intensity of 8 A will be referred to as 24 N, so that a consistent unit can be used in the discussion and for the variable of intensity in the regressions.

Surface roughness was measured after shot peening using an Alicona G4 optical profilometer, at three locations near mid gage for each specimen. Surface residual stress and x-ray peak width were measured by Lambda Technologies of Cincinnati, Ohio at four angular locations of 0°, 90°, 180°, and 270° around the middle of the gage section for one fatigue specimen with each shot peening condition. The (311) reflection of Mn radiation was used for all measurements. One of these locations was then subjected to repetitive sequences of electro-polishing to remove a surface layer of about 25 µm depth, and then again measuring residual stress and peak width. The change in residual stress due to this removal of material was accounted for using the equation recommended in Reference 17. This allowed determination of residual stress and peak width as functions of depth on all specimens. X-ray peak width has been correlated with cold work plasticity in many studies (Ref. 6). For the present conditions, a peak width of 3.0° corresponded to cold work of 1.9 percent in the test material.

Fatigue tests were performed at room temperature and 704 °C in a closed-loop servo-hydraulic testing machine using resistance heating and an axial extensometer. Each test was conducted with total strain controlled using a triangular waveform to produce a constant total strain range at a frequency of 0.33 Hz. The fatigue tests were performed with a total strain range ($\Delta\epsilon_t$) of 0.78 percent, and a strain ratio of minimum/maximum strain (R_ϵ) of zero. This generated maximum and minimum stresses that averaged 1083 and -596 MPa, respectively, at room temperature. Tests at 704 °C were consistently heated from room temperature in 75 min., cycled, and then consistently cooled in about the same time interval by opening and pivoting away the clamshell furnace. Maximum and minimum stresses that averaged 984 and -478 MPa, respectively, were generated in fatigue cycles at 704 °C.

A transverse section of the gage remote from the electro-polishing was also removed and metallographically mounted and polished. Sections were swab-etched for about 45 s using Waterless Kalling's reagent to delineate grain boundaries for optical microscopy, and measurements of linear intercept grain size per ASTM E112-13.

Statistical analyses of test results were performed using JMP®(SAS Institute). Linear regression equations were derived using stepwise selection of terms, with variables selected having at least a 90 percent probability of significance. When multiple variables were significant, the resulting regression equation was expressed with the variables in standard form, and also with each variable (V) scaled to lie between -1 and +1 by subtracting the mid value V_{mid} and then dividing by half of the range ΔV as follows:

$$V = (V - V_{mid}) / (0.5 * \Delta V)$$

This *scaled* regression equation allowed comparison of the strength of the effect produced by each significant variable in the regression equation, as indicated by the relative magnitude of each variable's coefficient. The coefficient of determination, adjusted to account for the number of variables (R^2_{adj}), was used to describe how much of the variation in response was accounted for by the equation, and the square root of the sum of the square of the remaining error in fitting each data point (rms Error) was used to

describe how much of the variation in response remained unaccounted for. This simple regression analysis was used to identify significant variables, determine their effects, and to compare their relative influences, but not to imply that each significant variable conclusively had a linear effect on the response. Further testing at several levels of each significant variable would be necessary to discriminate the linear or non-linear relationship for each variable.

Results and Discussion

Test Material

Mean linear intercept grain size of the ME3 test material was 24 μm , as shown in Figure 1(a). The machining of specimens by low stress grinding and polishing in the axial direction produced very fine polishing grooves in the axial direction of the gage section's surface, Figure 1(b).

Initial Stress and Peak Width Introduced by Shot Peening

Screening tests of shot peening conditions were first performed on specimens with no heating or fatigue cycles. Typical SEM images of the surfaces after varied shot peening conditions are compared in Figure 2. The shot peened surfaces were uniform for fixed shot peening conditions, eliminating the strong texture in the axial direction from the final machining step of longitudinal polishing. The shot peened surfaces had undulating, dimpled textures, with folds of material ("laps") sometimes occurring at the edges of dimples, both features more noticeable after shot peening at higher intensities.

Roughness varied among the shot peening conditions as shown in Figure 3. R_a , the arithmetic average of all vertical deviations from the mean and R_z , the vertical distance from the highest peak to deepest valley measured for different measurement lines and then averaged, are illustrated schematically in Figure 3. Both of these roughness parameters varied with shot peening conditions. R_a only slightly increased in going from the gentlest to most severe shot peening conditions, while R_z increased more substantially. Linear regression indicated R_a and R_z each varied with the cube root of intensity, according to the relationships where I is shot peening intensity having values of 8, 16, or 24 (Table 1):

$$R_a(\mu\text{m}) = 0.20 + 0.96 * I^{1/3} ; R_{\text{adj}}^2 = 0.60, \text{rms Error} = 0.31 \mu\text{m}$$

$$R_z(\mu\text{m}) = 1.06 + 3.93 * I^{1/3} ; R_{\text{adj}}^2 = 0.56, \text{rms Error} = 1.39 \mu\text{m}$$

Other comparisons of shot peening conditions versus roughness of disk superalloys have shown roughness to increase with increased intensity of shot peening, for example in Reference 12.

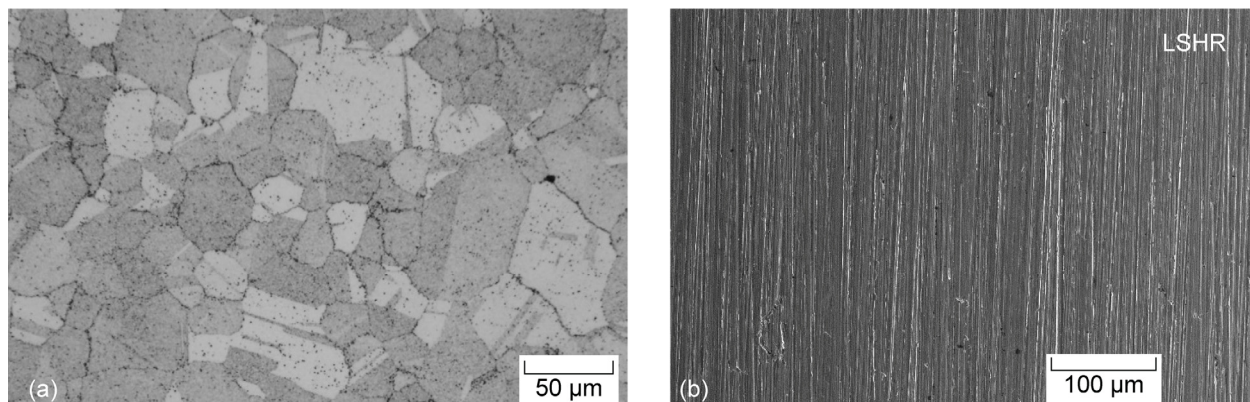
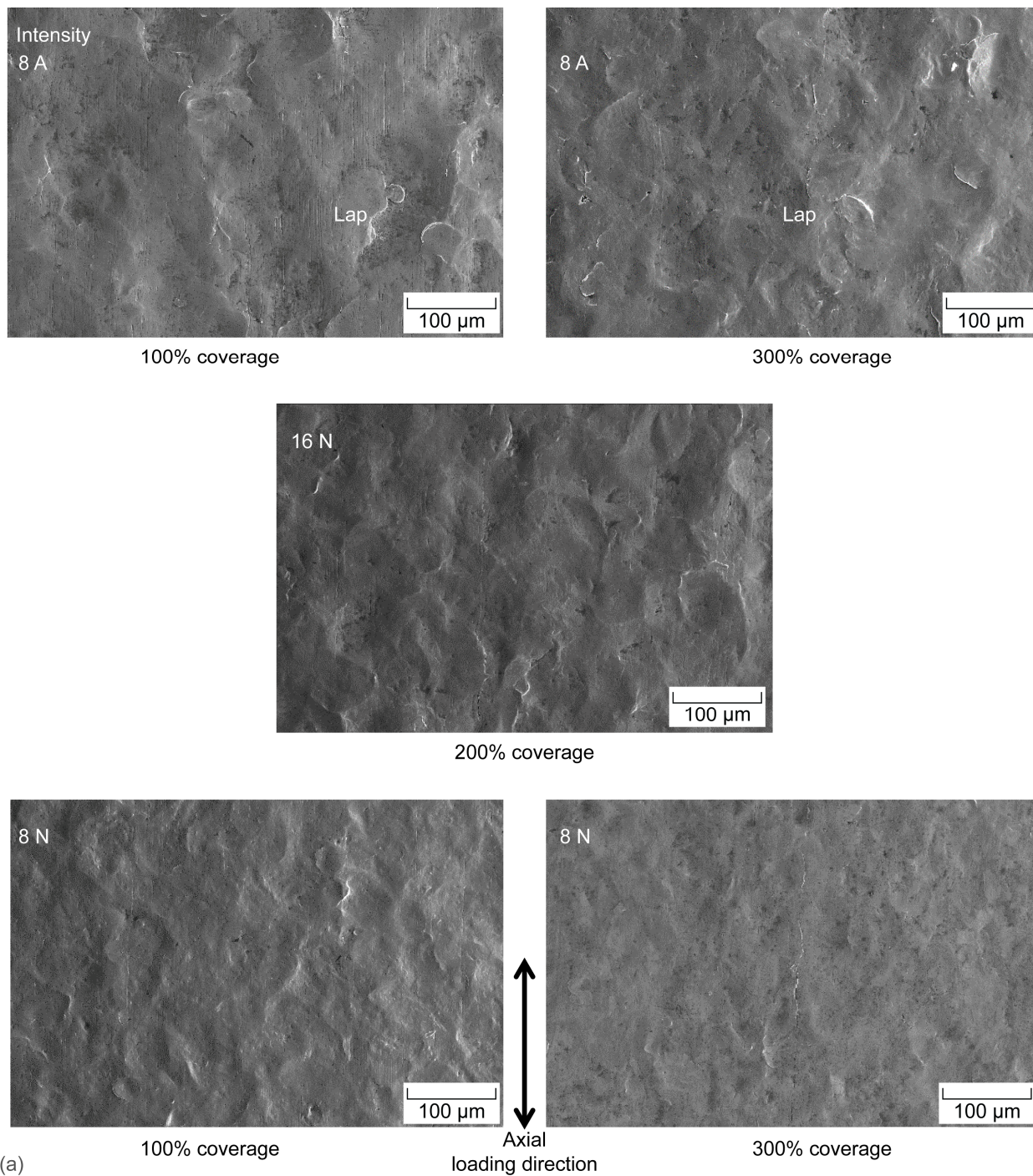


Figure 1.—(a) Typical microstructure, having mean linear intercept grain size of 24 μm . (b) Typical surface of low stress ground and longitudinally polished gage section, with axial loading direction oriented vertically.



(a)

Figure 2.—(a) Scanning electron microscope (SEM) images showing typical surface of shot peened gage section for varied shot peening intensity and coverage.

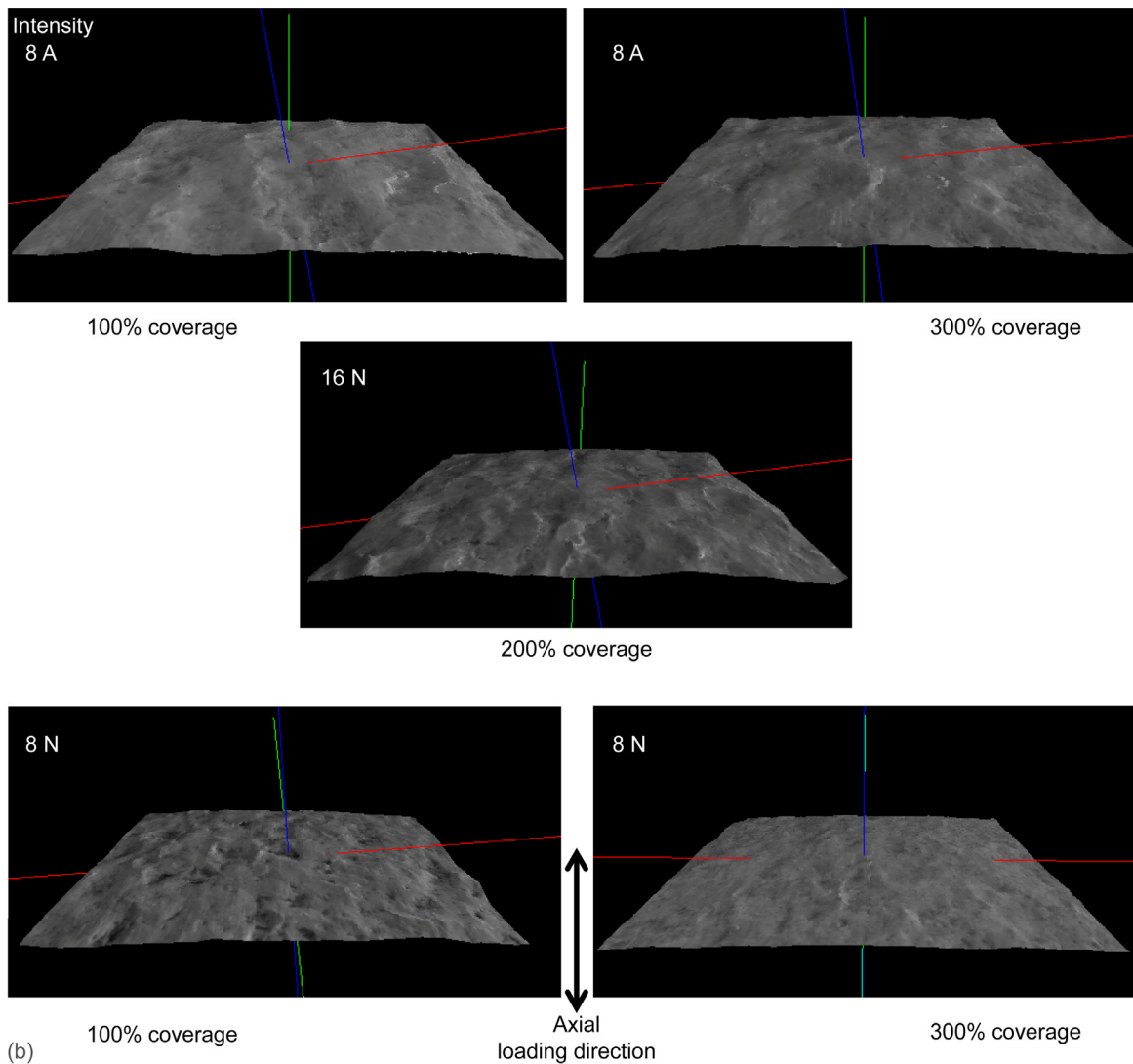


Figure 2.—(b) Three-dimensional representations reconstructed from stereo pairs of SEM images showing typical surface of shot peened gage section for varied shot peening intensity and coverage.

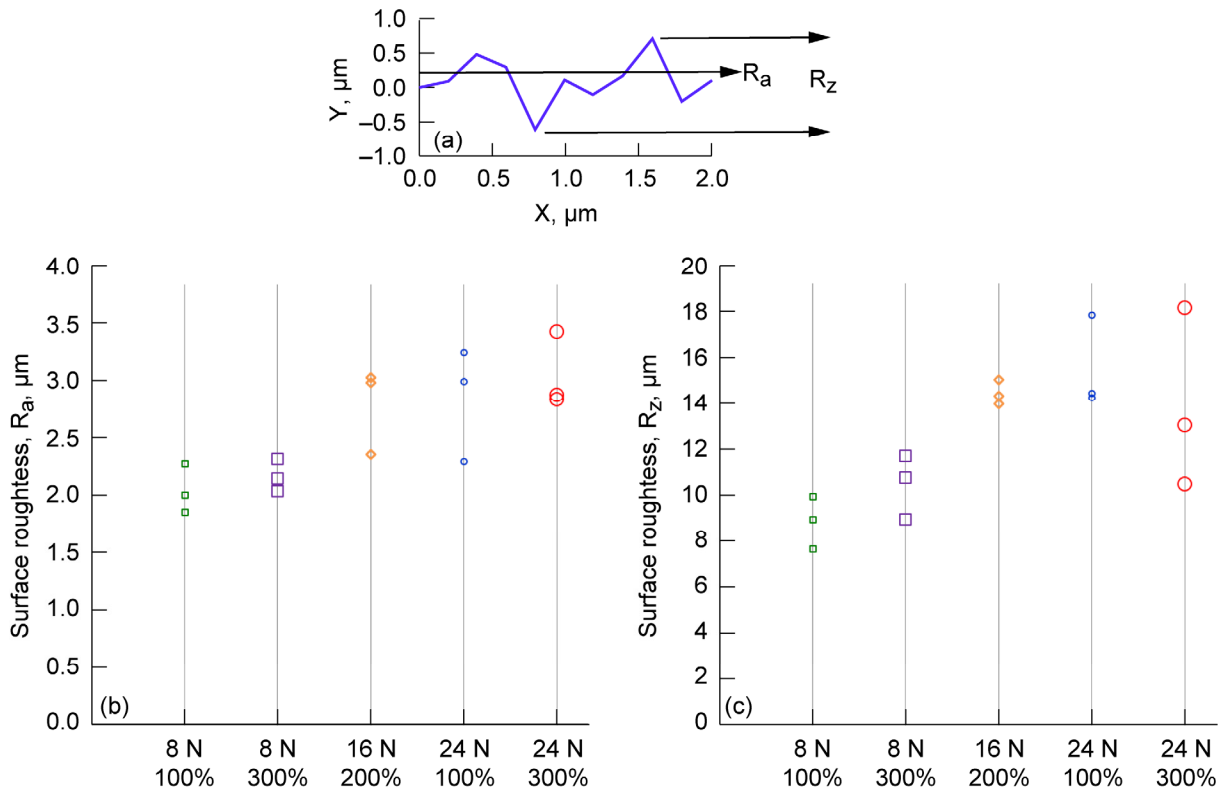


Figure 3.—Arithmetic average linear roughness (R_a) and peak-valley linear roughness (R_z) for surfaces subjected to varied shot peening intensity and coverage. Roughness clearly increased with shot peening intensity.

Axial residual stress (σ_{surf}) and associated peak width at half maximum intensity measured at the surface ($\text{PWHM}_{\text{surf}}$), the latter reflecting the extent of cold work, also varied with shot peening conditions of intensity (I) and coverage (C), Figure 4. The regression variables are listed in Table 1. Stepwise linear regression analyses indicated a relationship for axial residual stress of:

$$\sigma_{\text{surf}}(\text{MPa}) = -1778.1 + 222.1 * I^{1/3} + 0.38 * C;$$

$$\sigma_{\text{surf}} = -1156.2 + 98.2 * I^{1/3} + 38.0 * C \text{ (Scaled)}$$

$$R^2_{\text{adj}} = 0.88, \text{ rms Error} = 35.2 \text{ MPa}$$

This indicated the compressive residual stress measured at the surface decreased in magnitude, becoming more positive, with increasing intensity, and with increasing surface coverage. The cube root of intensity gave a slightly better fit than linear intensity, and so was used here. The *scaled* form of this equation, using scaled variables listed in Table 1, indicated intensity had a stronger effect than coverage. Studies of other finer grain disk superalloys (Ref. 18) have also shown the compressive residual stress measured at the surface was strongly related to shot peening intensity, yet the influence of coverage was not clear in those cases.

Conversely, the peak width at half maximum intensity (PWHM) measured at the surface increased modestly in magnitude when going from the lowest to the highest intensity, and from lowest to highest coverage. Peak width varied here according to the derived regression equation:

$$\text{PWHM}_{\text{surf}}(^{\circ}) = 4.126 + 0.025 * I + 0.002 * C;$$

$$\text{PWHM}_{\text{surf}} = 4.846 + 0.201 * I + 0.158 * C \text{ (Scaled)}$$

$$R^2_{\text{adj}} = 0.66, \text{ rms Error} = 0.166 ^{\circ}$$

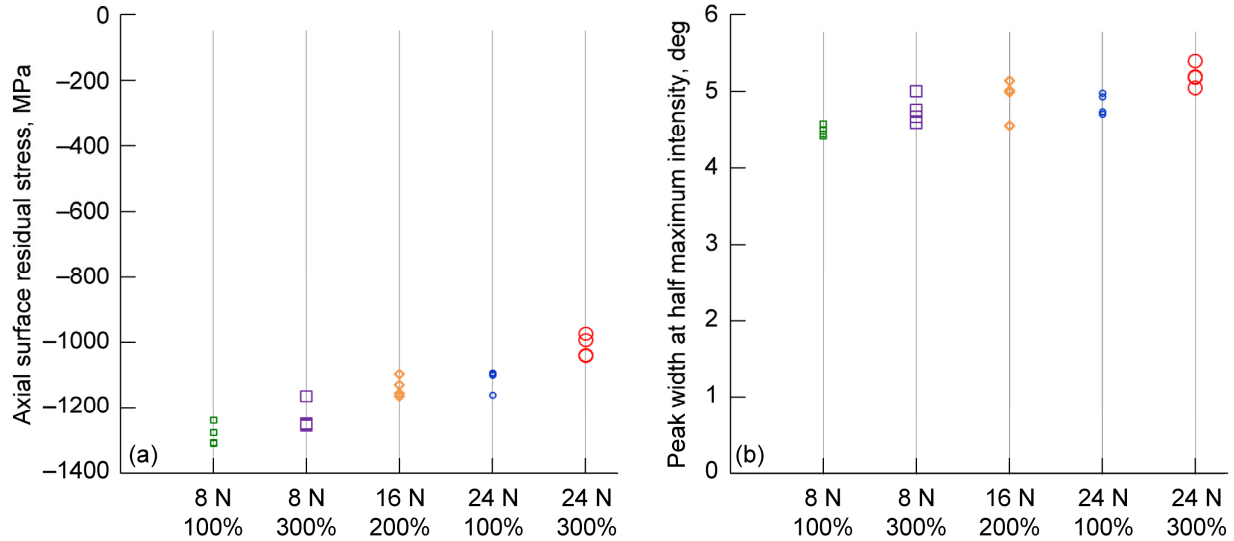


Figure 4.—Axial surface residual stress and peak width at half maximum intensity for varied shot peening intensity and coverage. Axial residual stress at the surface decreased in magnitude with increasing intensity and coverage, while peak width correspondingly increased.

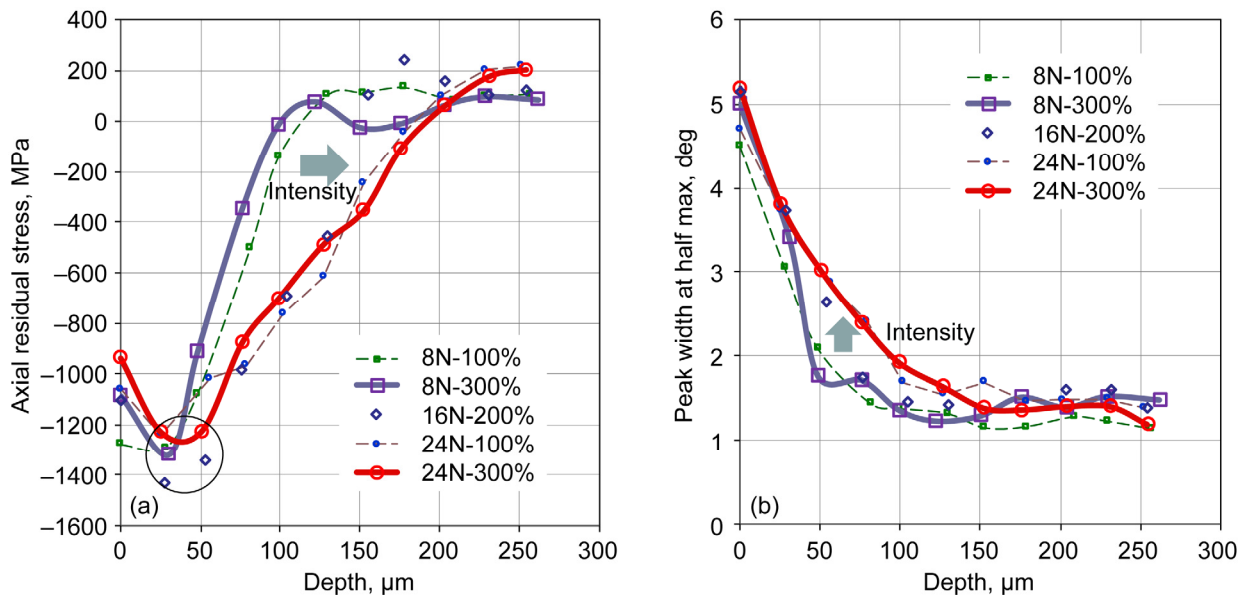


Figure 5.—Axial residual stress and peak width at half maximum intensity versus depth for varied shot peening intensity and coverage. Maximum compressive residual stresses were comparable, while depth of compressive stress clearly increased with increasing intensity. Peak width also appeared to increase with intensity.

The *scaled* form of this equation, using the scaled variables listed in Table 1, indicated intensity had a stronger effect than coverage on peak width, which is indicative of cold work. Other comparisons of shot peening conditions versus cold work generated at the surface of disk superalloys have shown coverage to have a predominant effect, rather than intensity (Ref. 18).

Axial residual stress and peak width are shown as functions of depth for each of these shot peening conditions in Figure 5. Compressive residual stress increased in magnitude at a depth of near 30 μm , then decreased going further in. This initial increase in magnitude of compressive stress with depth was largest for the case of 24 N – 300 percent, and was only very minor for 8 N – 100 percent. This resulted in maximum compressive residual stress occurring slightly below the specimen surface for many shot

peening conditions, and becoming comparable there. Regression analysis indicated no significant effect of intensity or coverage on the resulting maximum compressive residual stress, for the present conditions. Other comparisons for finer grain disk superalloys have also shown the maximum compressive residual stress did not vary strongly over even more widely adjusted shot peening conditions (Ref. 18).

Yet, the depth at which compressive residual stresses decay to zero (“depth of compression”) did vary with shot peening conditions, and clearly increased with intensity in Figure 5. The associated linear regression relationship for depth (D) of compression is:

$$D (\mu\text{m}) = 94.49 + 3.28 * I - 0.13 * C + 7.81 \cdot 10^{-3} * I * C;$$

$$D = 147.0 + 38.75 * I + 6.25 * I * C \text{ (Scaled)}$$

$$R^2_{\text{adj}} = 0.99, \text{ rms Error} = 2.96 \mu\text{m}$$

This indicated depth of compression increased with increasing shot peening intensity, and increased somewhat less so with combined high intensity and high coverage. The *scaled* form of this equation, using the scaled variables listed in Table 1, indicated intensity had the strongest influence on depth of compression. Peak width correspondingly decreased with depth, and leveled off at a depth consistent with this depth of compressive residual stresses. Yet at intermediate depths, the magnitude of peak width increased with increasing intensity. Studies of other coarse and fine grain disk superalloys (Refs. 14 and 18) have also shown the depth of compressive residual stresses was strongly related to shot peening intensity, but the influence of coverage was not reported in those cases.

Residual Stress and Peak Width After Subsequent Temperature and Fatigue Cycles

While shot peening intensity and cold work had significant influences on initial residual stress and peak width, these values changed substantially with subsequent fatigue and temperature excursions. The effects of temperature and fatigue cycles were first screened after shot peening at the mid-level conditions of 16 N intensity and 200 percent coverage, and the resulting residual stress and peak width measured as functions of depth are shown in Figure 6. A single temperature excursion up to 704 °C and back down to room temperature, taking about 150 min., induced a substantial reduction in the magnitude of compressive residual stresses at and beneath the surface. However, a single fatigue cycle at 704 °C, taking 3 s, produced the largest reductions in magnitude of residual stresses. Yet, stresses did not continue to change so much with more fatigue cycles, but became more stable. Hence, a single fatigue cycle was used to capture this large effect of fatigue at 704 °C, while minimizing cumulative time at the cyclic tensile mean stress generated by fatigue cycling. The latter could produce confounding cumulative stress relaxation, to relieve this cyclic tensile mean stress.

The magnitude of compressive residual stress at the surface was decreased by fatigue cycles and high temperature excursions for all of the shot peening conditions, with fatigue at high temperature again producing the largest reductions. Axial residual stress and associated peak width at half maximum intensity at the surface are compared for all of the shot peening conditions after single temperature and fatigue cycles in Figure 7. A single fatigue cycle at room temperature decreased the as-shot peened magnitude of compressive residual stress by about 30 percent, attributable to plastic deformation. A single temperature excursion to 704 °C decreased this magnitude by near 50 percent, attributed to stress relaxation. Combining these effects, a single heat up to 704 °C and fatigue cycle at 704 °C decreased this magnitude for all shot peening conditions by 80 to 90 percent. Yet, due to the variations in as-shot peened stresses previously described, varied shot peening conditions had some effects on remaining stresses, with the combination of lowest intensity and coverage (8 N – 100 percent) having the largest remaining magnitude of compressive stress, and the combination of highest intensity and coverage (24 N – 300 percent) having the smallest remaining magnitude of compressive stress.

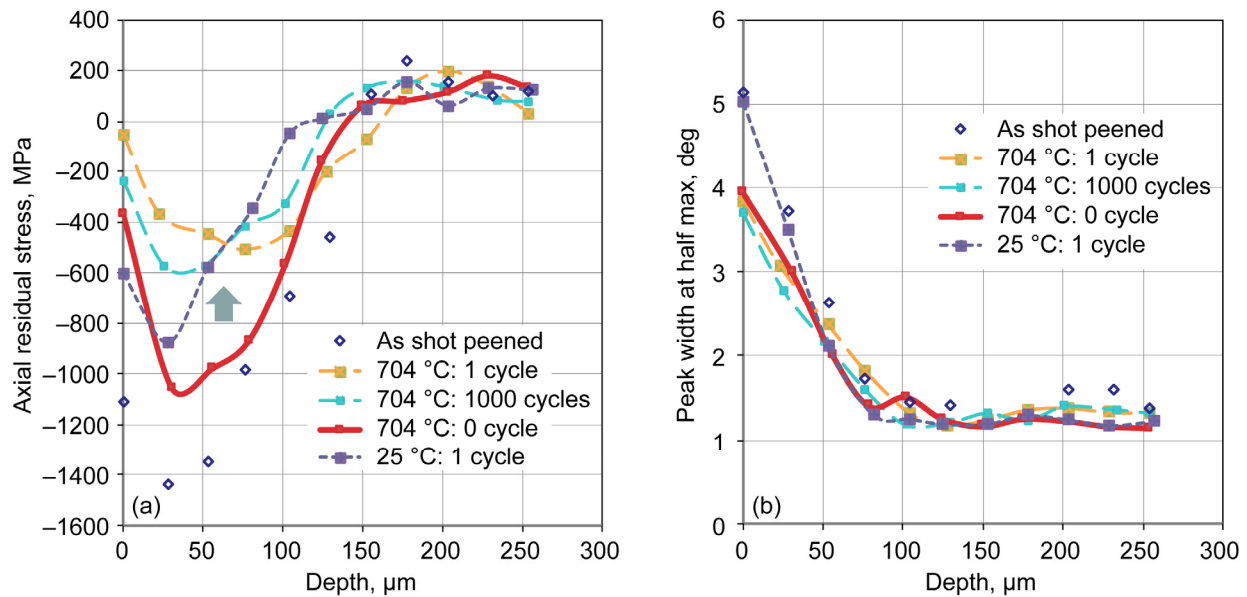


Figure 6.—Axial surface residual stress and peak width at half maximum intensity versus depth for mid-levels (16 N-200%) of shot peening intensity and coverage, after temperature and fatigue cycles. A fatigue cycle at 704 °C produced the largest change in residual stress, but stresses did not change much with more fatigue cycles. Peak width was reduced at 704 °C.

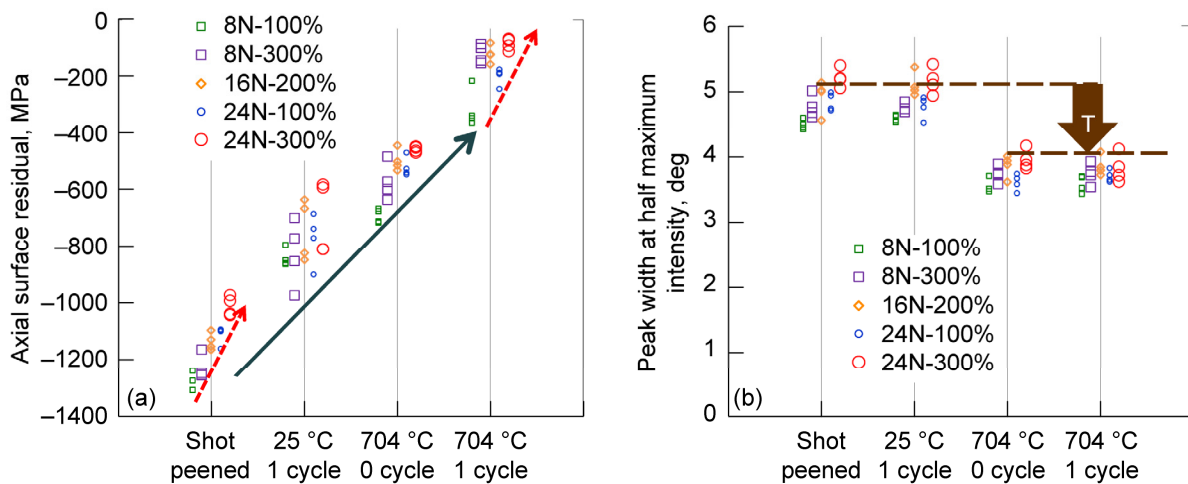


Figure 7.—Axial surface residual stress and peak width at half maximum intensity for varied shot peening intensity and coverage, after single temperature and fatigue cycles. The magnitude of compressive residual stress at the surface was decreased most by a fatigue cycle at high temperature, with comparable reductions for all shot peening conditions. Peak width was decreased by cycles at high temperature.

All these effects on residual stresses could be compared by running stepwise linear regression on shot peening conditions as before, but with the additional variables of temperature (T) and fatigue cycle (F) also included. Here, linear intensity was found to give satisfactory regression results, without a cube root transformation. This produced for remaining surface residual stress the regression equations:

$$\sigma_{\text{surf}}(\text{MPa}) = -1407.5 + 10.6 * I + 0.3 * C + 0.8 * T + 462.3 * F - 5.1 * I * F + 4.5 \times 10^{-4} * C * T;$$

$$\sigma_{\text{surf}} = -662.4 + 64.3 * I + 45.8 * C + 304.2 * T + 190.0 * F - 20.6 * I * F + 15.4 * C * T \text{ (Scaled)}$$

$$R^2_{\text{adj}} = 0.97, \text{ rms Error} = 62.2 \text{ MPa}$$

The regression indicated that the residual stress measured at the surface decreased in magnitude, becoming more positive, with increasing linear intensity, increasing coverage, increasing temperature and with a fatigue cycle. The *scaled* form of this equation, using the scaled variables listed in Table 1, indicated that temperature had the largest effect on residual stress, followed by a fatigue cycle, then shot peening intensity and coverage. The interaction terms indicated the large effect of temperature was modestly reduced with lower shot peening coverage, while the large effect of a fatigue cycle was modestly reduced with higher shot peening intensity. Other comparisons (Refs. 9, 18, 10, 19, and 20) of shot peening residual stresses before and after temperature cycles have shown similar reductions in magnitude of compressive residual stresses measured at the surface, which have been related to enhanced stress relaxation of microstructures having highest prior cold work (plasticity) from the shot peening.

The large effect of a single fatigue cycle in reducing the magnitude of compressive residual stresses and the smaller effect of subsequent cycles, was previously observed in studies of fine grain IN100 (Ref. 10) and fine grain Udimet 720Li (Ref. 21), though for larger applied cyclic strain ranges. Yet, these reductions due to fatigue cycles can be challenging to model (Ref. 22), as they can be dependent on plasticity generated during the shot peening as well as that generated in the subsequent fatigue cycles, and are also influenced by time-dependent stress relaxation of microstructures having gradients of prior plasticity (cold work) from the shot peening.

Peak width measured at the surface was also affected by temperature and fatigue cycles, and so was also re-evaluated with the addition terms of temperature (T) and fatigue cycle (F) to compare all effects. This produced the regressed relationships:

$$\text{PWHM}_{\text{surf}}(^{\circ}) = 4.416 + 0.015 * I + 0.001 * C - 0.002 * T ;$$

$$\text{PWHM}_{\text{surf}} = 4.297 + 0.117 * I + 0.125 * C - 0.562 * T - 0.058 * I * T \text{ (Scaled)}$$

$$R^2_{\text{adj}} = 0.66, \text{ rms Error} = 0.166$$

This regression again indicated peak width increased with intensity and coverage, but then was reduced by temperature. The *scaled* form of this equation, using the scaled variables listed in Table 1, indicated that temperature in fact had the largest effect, followed by shot peening coverage and intensity. The large effect of temperature was modestly reduced for lower shot peening intensity. Similar reductions in cold work induced by high temperature excursions, as reflected here by x-ray peak width, have been reported for other superalloys (Refs. 10 and 13). This has been related to dislocation recovery processes.

Residual stress and peak width were measured as functions of depth for all shot peening conditions after a single subsequent fatigue cycle at 704 °C, as shown in Figure 8. For all shot peening conditions, the magnitudes of compressive residual stresses also decreased at and beneath the surface after the fatigue cycle at 704 °C. Yet, peak width only decreased very near the surface. The depth of compression still remained higher for conditions having high intensity shot peening.

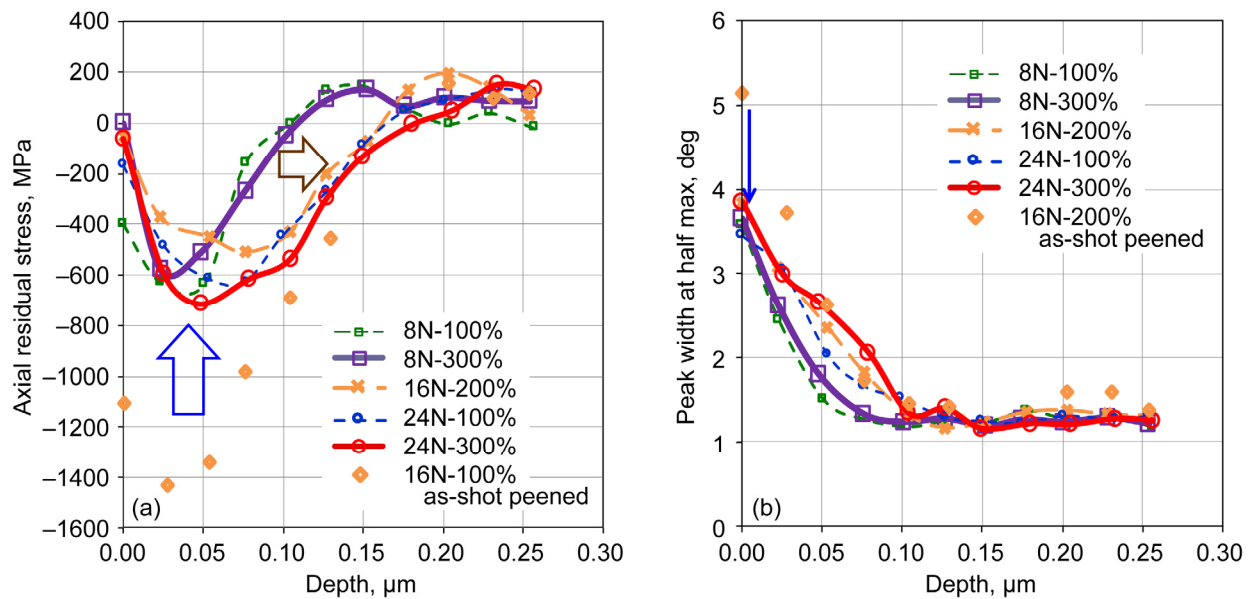


Figure 8.—Axial surface residual stress and peak width at half maximum intensity versus depth for varied shot peening intensity and coverage, after a single fatigue cycle at 704 °C. For all shot peening conditions, the magnitudes of compressive residual stresses decreased at and beneath the surface after the fatigue cycle at 704 °C; yet peak width only decreased near the surface. The depth of compression remained higher after shot peening at high intensity.

Summary and Conclusions

The relative magnitudes and stabilities of residual stresses, cold work as measured by peak width, and roughness introduced by shot peening of disk superalloy ME3 were studied, after shot peening and also when subjected to fatigue and high temperatures. Relatively low levels of coverage were applied, in hopes of minimizing stress relaxation due to excessive cold work. Compressive residual stress and peak width reflecting cold work were moderately sensitive to the varied shot peening conditions employed. However, the residual stresses were more strongly influenced by temperature and fatigue excursions. It could be concluded from this work that:

- 1) Shot peening can make average roughness more uniform and non-directional, in comparison to as-directionally machined surfaces, but both average and maximum roughness can increase with increasing shot peening intensity.
- 2) While higher shot peening intensity and coverage can increase the depth of compressive residual stresses, low intensity and coverage gave the highest magnitude of compressive residual stress at the exposed surface, both before and after temperature and fatigue cycles.
- 3) The magnitudes of these beneficial stresses were reduced similar amounts for all tested shot peening conditions, by high temperature and fatigue cycles.
- 4) Moderately reduced peak width reflecting lower cold work can be attained by combining low shot peening intensity and low coverage, yet the resulting compressive residual stresses are still significantly decreased in magnitude by temperature and fatigue cycles.
- 5) The priority of magnitude of compressive stresses remaining at an exposed surface versus depth of compressive stresses extending in from the surface is a key consideration, as no combination of applied shot peening conditions was identified which could maximize both responses at the same time, either before or after temperature and fatigue cycles.

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